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ADHESIVE BONDED DOUBLER FOR H-3 HELICOPTER BLADE SPAR

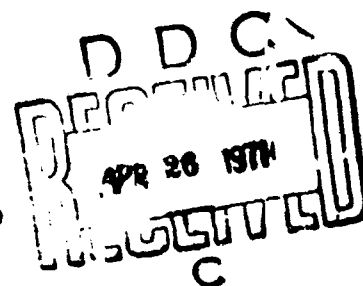
THEODORE J. REINHART, JR.

TECHNICAL REPORT AFML-TR-70-241

FEBRUARY 1971

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69

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**ADHESIVE BONDED DOUBLER FOR
H-3 HELICOPTER BLADE SPAR**

THEODORE J. REINHART, JR.

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FOREWORD

This report was prepared by the Materials Engineering Branch, Materials Support Division, Air Force Materials Laboratory (LAE), Wright-Patterson Air Force Base, Ohio. This work was initiated under Project No. 7381, "Materials Applications," Task No. 738101, "Exploratory Design and Prototype Development," and Task No. 738108, "Application of Materials and Processes for Tactical War Support," with Mr. T. J. Reinhart, Jr., Project Engineer.

The work by the University of Dayton (Messrs. McKiernon and Marton) in preparation of test specimens, conduct of static, and fatigue testing is gratefully acknowledged. Messrs. M. Chopin and D. Hansen of the V/STOL Propulsion Branch, Directorate of Propulsion and Power Subsystems Engineering of the Aeronautical Systems Division (ASD) provided valuable assistance in their review of the program plan and the accomplishment of the liaison and coordination of the various ASD offices and the laboratories involved in this program.

This report covers work conducted from 15 April 1970 to 31 August 1970. The manuscript was released by the author in September 1970.

This technical report has been reviewed and is approved.

A. Olevitch

A. OLEVITCH
Chief, Materials Engineering Branch
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ABSTRACT

An in-house program has been initiated in order to demonstrate the feasibility of the use of an adhesive bonded, structural doubler to provide a field fix solution to the problem of crack formation in the rivet holes of the tip of the CH/HH-3C main rotor spar. The program is being conducted in the following phases:

- I Doubler Design and Analysis
- II Subscale Specimen Testing
- III Stub Blade Fatigue Testing
- IV Whirl Tower Blade Testing
- V Field Installation Kit

The program is designed to demonstrate the effectiveness and reliability of an adhesive bonded doubler in the elimination of crack formation and growth due to stress concentration in a metallic substructure. It is to develop quantitative design information to enable optimization of the doubler and to develop methods for the field application of doublers to the H-3 spar.

A combined analytical-experimental program is in progress as described previously. A preliminary mechanical and thermal stress analysis has shown that a boron epoxy laminate based on the 3M boron prepreg material SP 272 or the Narmco 5505 material with a fiber orientation of $\pm 5^\circ$ to the blade spanwise direction should provide the lightest weight, thinnest, and most reliable doubler compared to any other available material, except perhaps beryllium sheet material. The doubler required

AFML-TR-70-241

to retard crack formation and growth in the 0.160-inch thick, 6061-T6, aluminum spar is about 0.095-inches thick by 6-inches wide by 17-inches long. The adhesive selected for bonding the doubler is Bloomingdale's FM-137. This adhesive is a corrosion-resisting nitrile modified epoxy that has good wetting characteristics, cures in about 30 minutes at 225°F, and requires only minimal curing pressure (8-12 PSIG). The aluminum surface preparation selected is the 3M degreasing cleaner 3911. The weight of the boron epoxy doubler plus adhesive, not including, erosion protection is about 0.8 pounds.

The mechanical and thermal loads induced in the doubler and the adhesive bond under the most severe conditions, operating at -65°F, are 44,500 PSI compression and 1050 PSI shear, respectively. Work is in progress to perform a finite element stress analysis on the bonded doubler specimen in order to obtain a more accurate picture of the stresses and strains in the bonded assembly.

Specimen fatigue testing has demonstrated that a boron epoxy bonded doubler is very efficient in reducing the rate of crack growth in pre-cracked specimens. One specimen that was fatigue pre-cracked prior to bonding on the doublers has survived 1.2×10^7 fatigue cycles of 5000 PSI \pm 4500 PSI net stress without failure in the doubler area. This was an extremely severe condition. Successful doubler performance on this pre-cracked specimen practically ensures successful performance on specimens without cracks.

AFML-TR-70-241

Work is in progress to develop the actual doubler configurations that will be applied to the stub blades and to establish the manufacturing and quality assurance procedures required.

An Air Force Materials Laboratory developed thermo-photochromic coating has been successfully utilized on subscale specimens to detect flaws in the bond area of the doubler. This NDT method is simple, rapid, and is sufficiently sensitive for use in doubler inspection in the field. Inspection procedures using this technique will be further developed and defined as we proceed in the program.

TABLE OF CONTENTS

SECTION	PAGE
I INTRODUCTION	1
II PHASE I, DOUBLER DESIGN AND ANALYSIS	5
III PHASE II, SUBSCALE SPECIMEN TESTING	9
IV PHASE III, STUB BLADE FATIGUE SPECIMENS	15
V PHASE IV, APPLICATION OF BONDED DOUBLERS TO WHIRL TOWER TEST BLADES	16
VI PHASE V, DOUBLER FIELD INSTALLATION KIT	17
VII DISCUSSION AND CONCLUSIONS	18
REFERENCES	40
APPENDIX	41

ILLUSTRATIONS

FIGURE		PAGE
1	6061-T6 Specimen with Ten Hole Rivet Pattern	29
2	6061-T6 Specimen with Four Hole Rivet Pattern	30
3	Dimensional Drawing of Fatigue Test Specimens	31
4	Typical Fatigue Failure of Control Specimen	32
5	Grip Failure in Four Hole Fatigue Test Specimen	33
6	Application of Photo-Thermochromic NDT Coating to Specimen B.O. 6.14 in Schenck Tester	34
7	Drawing of Specimen with Loaded Holes, Four Hole Pattern	35
8	Fatigue Failure, Graphite Doubler Bonded to One Side Only	36
9	Specimen B.O. 6.14, Boron Epoxy Doubler Both Sides Specimen Pre-Cracked Prior to Bonding Doublers	37
10	Drawing of H-3 Spar Tip	38
11	Mechanical Action of Bonded Doubler in Retarding Crack Growth in Metal	39
12	Double Strap Specimen	55

TABLES

TABLE		PAGE
I	Subscale Specimen Test Plan	24
II	S/N Data on Four Hole Fatigue Specimens	25
III	Test Laboratory Data Sheet on Four Hole Fatigue Specimens	26
IV	Doubler Laminates and Bonded Fatigue Specimens Produced to Date	27
V	Program Schedule	28
VI	Doubler Parameters (4.75 Inches Long) for Four Hole Specimen	53
VII	Properties of $\pm 5^\circ$ Graphite Epoxy Doubler	54
VIII	Properties of $\pm 5^\circ$ Boron Epoxy Doubler	54

SECTION I

INTRODUCTION

At the request of SDQH, the Helicopter Program Division of the Combat Systems Program Office, a program was initiated to determine the feasibility of the use of an adhesive bonded doubler to provide an early and interim field fix solution to the problem of tip crack formation in CH/HH-3C helicopter main rotor spar.

The CH/HH-3C helicopter which is being used in SEA, in a vital rescue role, has a severe problem in the form of fatigue cracks in the tip portion of the main rotor spar. Numerous cracks have been detected in service. The detection of a crack is cause for blade replacement because in most cases spar failure, while in flight at any significant altitude would be catastrophic.

The present blade design involves a multiplicity of rivet holes through the spar. These holes and rivets are necessary for retention of the leading edge weight, balance and tracking weights, and tip and tip cap.

The fatigue cracks have been formed as a result of higher than anticipated flight stresses in the tip region of the spar. The cracks originate at, and are caused by the fine feather edge of the counterrunk rivet holes. This problem is particularly critical in that these cracks

are forming in a region outboard of the BIM* seal. At the present time, the continued operation of the helicopter is permissible only with visual checks for cracks every seven hours and fluorescent dye penetrant inspections every 25 hours of flight. These inspections presently impose a severe maintenance burden on the users.

The proposed solution, consisting of an adhesive bonded doubler covering the distressed area of the spar is not a new or novel approach to the problem. Adhesive bonded doublers have been utilized in the repair of aircraft structural members, spars, beams, and sandwich panels for quite some time. Needless to say, the applications of a bonded doubler to the tip area of a helicopter blade is perhaps the most critical and challenging of all bonded doubler applications. The attachment of a doubler to the tip of the CH/HH-3C blade spar posed many problems for which we could find no ready answers. In addition, literature surveys disclosed a complete lack of test data and information from which we could establish quantitative design information.

Ideally, the doubler should be a lightweight, very high modulus material, in order that the doubler be as thin as possible to prevent severe performance degradations that result from changes in the blade contour. The most promising material presently available was the Celanese graphite fiber (75×10^6 PSI modulus) epoxy resin laminate.

*BIM- Blade Inspection Method. A means of detecting fatigue cracks in the hollow structural spar by pressurizing with nitrogen and monitoring retention of pressure during operation.

A preliminary analysis of the problem performed on a strength (and stiffness) of materials basis indicated that the graphite epoxy composite materials would provide the lightest and thinnest doublers. The analysis also indicated that the thermal stresses induced, even with a room temperature curing adhesive, were sufficiently high to cause serious concern for the reliability of the doubler and the bond to the spar.

Stainless steel makes an ideal doubler. It needs no erosion protection, is easily fabricated and bonded, and thermally induced stresses are minimal. The weight of the required thickness of stainless steel, however, was excessive and could not be tolerated by the rotor system.

The properties of cross rolled beryllium sheet make it an interesting candidate for this application, however, initial efforts will be primarily on the boron epoxy composites. Beryllium will be investigated as a back up material in the event the thermal stress problem with the epoxy composites is too severe.

Next to the graphite composites, the boron epoxy composites provide lightest and thinnest doublers. The analysis showed that the thermal stresses involved due to the difference in the thermal expansion of the boron epoxy laminate and the aluminum spar were high. However, due to the other attractive properties of the laminate, work has proceeded with this material. Erosion protection would have to be provided because of the relatively low resistance of the laminate to rain and particle impact.

Since the application of a doubler to the blade tip will deny access to the spar for visual inspection, it becomes mandatory to ensure that a bonded doubler will, in fact, function reliably as long as it is bonded to the spar. The subscale test program and the stub and full blade fatigue tests are designed to demonstrate this reliability. In field NDT of the doubler to spar bond, integrity can be accomplished by the use of ultrasonics or the use of the Air Force Materials Laboratory developed photo-thermochromic coating system. Techniques and standards for both methods will be developed under this program.

SECTION II

PHASE I. DOUBLER DESIGN AND ANALYSIS

Preliminary calculations of the bonded doubler requirements, based on load inputs from ENJER, V/Stol Propulsion Branch, and Sikorsky indicated that stiffness was the critical design parameter and that the doubler thickness was inversely proportional to the modulus of the material utilized. Also, communications from Sikorsky indicated that it was desirable to keep the doubler as thin as possible. Doubler design calculations based on stainless steel, sheet and boron epoxy, and graphite epoxy laminates having ply orientation of $\pm 5^\circ$, and a stress limit of 5000 PSI (steady state plus vibratory) maximum in the aluminum showed that with a material modulus of 30 million PSI, the required doubler thickness was 0.095 inches for each 0.160-inch thickness of spar. This thickness is required only over the spar areas prone to cracking. The doubler thickness can be gradually decreased as we move away from these areas.

Stresses in the adhesive bond layer are governed by the length of the bond that we employ. Calculations show that with a one-inch overlap the adhesive stress due to applied steady state loads are less than 1200 PSI. Stresses in the boron epoxy composite doubler and adhesive due to the applied mechanical (steady state plus vibratory) loads are: 23,400 PSI tension and 1560 PSI shear, respectively.

An analysis was performed in order to determine the stresses that would be set up in the adhesive bond and the doubler as a result of the

differences in the thermal contraction (and expansion) characteristics of the various doubler materials with respect to the aluminum spar.

Calculations based on a temperature excursion from about 220°F (adhesive cure temperature) to -65°F, $\Delta T = 285^\circ\text{F}$ showed the stress buildup in the doubler and the adhesive to be as follows:

	<u>Stress in Doubler</u>	<u>Stress in Adhesive</u>
Stainless Steel	900 PSI compression	60 PSI (shear)
Graphite Epoxy	113,400 PSI compression	2300 PSI (shear)
Boron Epoxy	59,700 PSI compression	1050 PSI (shear)

Based on the analysis, the stainless steel is the most desirable doubler material. The boron epoxy doublers may be feasible, however, the graphite epoxy would no doubt fail in interlaminar shear or in the adhesive on temperature cycling.

The analysis was rerun on the graphite epoxy doubler, based on a RT cure (80°F). In this analysis the cool down to -65°F gives us a $\Delta T = 145^\circ\text{F}$. The resultant stress in the doubler and the adhesive were found to be 40,000 PSI compression and 800 PSI shear, respectively. The graphite epoxy seems feasible based on a room temperature curing adhesive system.

It should be understood that the thermally induced stresses are a severe case condition and that the actual environmentally induced stresses in the bonded assembly could be significantly less than shown here. The linear analysis utilized does not account for stress relief in the bond due to adhesive viscoelastic properties.

Based on the previous calculations, weight estimates were made of the bonded doublers (exclusive of adhesive) required for actual application to the blades. These weights are:

	<u>Total Weight Per Blade</u>
Stainless Steel	6.42 lbs
Boron Epoxy	1.60 lbs
Graphite Epoxy	1.31 lbs

These are the weights of doublers (top and bottom) of constant cross section 6 inches wide by 20 inches long. These weights can be reduced about 20% by doubler contouring and tapering.

Completion of Phase II fatigue testing will enable final design calculations and weight estimates to be made.

Considering the worst possible case where the applied mechanical loads and the thermally induced stresses are additive (operation at -65°F), the stresses in a boron epoxy doubler and the adhesive would be 44,500 PSI compression and 785 PSI shear. The stresses in the boron epoxy laminate are well within the material capabilities. The adhesive stresses for this case are well within the material capabilities. Unfortunately, the induced thermal stresses result in a high tensile stress in the aluminum which could jeopardize the use of the boron epoxy composite doubler.

Work is presently in progress to more accurately estimate the stress distribution in the doubler and in the adhesive, the affect of the stress

concentrations in the metal on the doubler performance, and the peak stresses in the doubler and the adhesive. Attempts to do this through computer methods described in Reference 3 and to set up a finite element analysis of the bonded doubler specimen are in progress.

The doubler and adhesive bond are designed to carry the entire tensile and bending loads on the spar tip should the aluminum spar fail via cracking. The detailed calculations performed to date are included in the Appendix.

SECTION III

PHASE II. SUBSCALE SPECIMEN TESTING

The subscale test program is designed to validate via the static and fatigue testing of test specimens, the preliminary doubler calculations, laminate material, adhesive selections, and doubler fabrication and bonding procedures as they have been presently established.

The 6061-T6 aluminum specimens of the ten hole configuration shown in Figure 1, were initially selected for this phase of the work. Photo-stress evaluations of the strain field in the test area, performed in-house, showed this rivet hole pattern to be unsuitable for our use. Subsequent discussions with Sikorsky personnel confirmed our findings.

The specimen was redesigned with a four hole rivet pattern shown in Figures 2 and 3. The specimens are 0.160-inches thick. The rivet holes and pattern are identical to those found in the H-3 rotor tip area.

A tentative program test plan is shown in Table I. This plan, of necessity, is quite flexible and changes will be made, as required, when dictated by our test results. The subscale testing program is very comprehensive and it is likely that we will be testing specimens well past the whirl tower testing of the doubler modified blades.

Fatigue testing is presently in progress on specimens of the four rivet hole configuration. Stresses of 5000 PSI mean and 4500 PSI alternating, based on the net cross-sectional area of the aluminum are

being applied. Tests are being conducted at room temperature on a 20 ton Schenck machine. Load cycles are being applied at a rate of 2000 cycles per minute.

Fatigue testing of the control specimens has been completed. Figure 4 shows the mode of failure that was typical of the control specimens. Cracking would invariably initiate at a burr, notch, or machining mark at the fine edge of the 5/16-inch diameter hole. This fine or sharp edge was caused by the countersinking operation and was purposely not removed for our testing in order that we might operate under extremely good crack producing conditions. The four control specimens, fatigue tested to date, average 1.6×10^5 cycles. Initially, specimens having doublers bonded to one side only were fabricated for fatigue testing. To date, seven specimens having bonded doublers have been fatigue tested. The detailed data are presented on Tables II and III. Due to the unsymmetrical loading of a specimen with a doubler on one side, these specimens all were subjected to bending during the fatigue test. As a result, they all failed in a crack propagation mode similar to the controls. They did, however, last much longer than the control.

As can be seen in Table II the control specimens are all closely grouped in the 1×10^5 to 2×10^5 cycles range. Specimens 6.11 and 6.12 were pre-cracked prior to doubler (one side only) application. As can be seen, specimens 6.11 and 6.12 failed early due to the severe bending introduced into the specimen.

Specimens 6.5 and 6.6 had doublers bonded to one side only. These specimens also underwent the severe bending but they were not pre-cracked. Therefore they survived quite a bit longer than the controls. Subsequent to the previous series of tests, doublers were bonded to both sides of the specimen in order to maintain symmetry and to eliminate the bending problems encountered in the initial specimens. Specimens now being tested have 0.046-inch doublers bonded to each side rather than an 0.095-inch doubler on one side.

To date, two specimens having doublers bonded to each side have been fatigue tested. Both specimens; one stainless, the other boron epoxy, failed in fatigue in the grip section at about eight million cycles. Figure 5 shows grip failures typical in specimens B.O. 6.8 and B.O. 6.14. It is intended that we will repair these specimens by bonding on 0.050-inch stainless doublers on each side of the grip area and continue the fatigue testing.

Specimen B.O. 6.14 was tested by coin tapping about every 500,000 cycles to see if any debonding could be detected. At about 7.5 million cycles a slight rattling sound was noticed as the specimen was tapped. An inspection, using the AFML NDT thermo-photochromic paint system, was conducted while the specimen was in the test machine and under load.

Figure 6 shows a photograph of the results of the testing. No voids, cracks, or delaminations were found. Closer inspection revealed that one corner of the specimen had worked loose in the grip area. This was the cause of the rattling on coin tapping examination.

Nondestructive inspection with the thermo-photochromic paint system is a simple and rapid procedure that can be accomplished quite easily. The specimen was coated with the NDT paint and allowed to dry. The coating was then developed (to a deep purple) via a brief exposure to ultraviolet light. The coated specimen was then heated very gently with a hot air gun. As can be seen, the four rivet holes which represent thermal discontinuities in the specimen show up very well. No other thermal discontinuities were found in the specimen.

Specimen B.O. 6.14 (Figure 6) had slots Eloxed into the rivet holes perpendicular to the applied load. Prior to bonding on the boron epoxy doublers, the Eloxed slots were fatigue pre-cracked by repeated loading in the Schenck machine. The fact that after bonding of the doublers, this specimen has at the present time, survived over eight million fatigue load cycles, indicates that this will be a very effective fix for the H3 spar cracking problem.

The Eloxed slots were about .005-inch wide and about 0.10-inches long. These slots did not show up under the NDT coating inspection because its resolution limit through the 0.046-inch thick boron epoxy laminate is estimated to be about 0.10 inches. Work on the second phase of the fatigue testing of specimens has begun. A specimen configuration has been designed in which all of the load is introduced into the aluminum through the rivet holes. Figure 7 illustrates the essential features of the proposed specimen. It is essentially a clevis arrangement which sandwiches a steel member between two aluminum members. The three pieces are riveted together and the boron epoxy doublers full thickness (.096-inches) will be applied to each aluminum face after installation of the

rivets. Materials for this specimen have been ordered and control testing should begin in the near future. Table IV shows a listing of the laminates and specimens with adhesive bonded doublers that have been prepared to date.

Figure 8 shows the failure of specimen B.O. 6.5 (graphite one side). In this, as in the other one-sided specimens, it was possible to watch the crack growth during the test. This failure was typical of all of the one-sided doubler specimens. As can be seen, the crack pattern is significantly different from that found in the control test specimens; thus indicating that a significant portion of the load is being carried by the doubler.

Figure 9 shows specimen B.O. 6.14 before testing; this specimen was Eloxed and the slots pre-cracked prior to application of 0.046-inch boron epoxy doublers to each side. The 6061-T6 aluminum surface was prepared using 3M degreasing cleaner 3911. The adhesive utilized was Bloomingdale BR 137-1 (corrosion resisting) film and was cured at 225°F for 60 minutes under about 12 PSIG pressure. The pre-cured boron epoxy doubler was prepared for bonding by removal of the peel ply. The boron epoxy doubler was fabricated using 3M SP-272 boron epoxy prepreg, according to the manufacturers recommending curing conditions. It is presently planned to utilize these materials throughout the remainder of the program. In order to verify the stress buildup, due to thermal expansion mismatch in a specimen having a graphite epoxy laminate doubler bonded to one side, a specimen was exposed to cyclic temperature excursions from RT to +180°F to RT to -65°F with half hour exposure at

AFML-TR-70-241

each condition. The specimen underwent severe bending due to the high expansion and contraction of the aluminum compared to the graphite. The specimen was restrained in the flat condition during the temperature cycling in order to allow the stresses to buildup. The specimen failed after about 50 of the above cycles were completed. The failure was partly interlaminar shear in the graphite epoxy and partly adhesion failure off the aluminum. The graphite epoxy laminate was fabricated from (G) (RT)-70-350A prepreg from the Celanese Corporation. The adhesive utilized was a RT cure, acrylate type, 1776B/A from the Lord Division of the Hughson Corporation.

Specimens with boron epoxy doublers will be given similar cyclic temperature exposures.

SECTION IV

PHASE III, STUB BLADE FATIGUE SPECIMENS

A stub (tip) blade section received from ENJER is presently being utilized to lay up the bonded doubler that will be utilized on the actual blade. Doubler shape, profile, and thickness are being determined. Pre-cut Mylar transparencies of each ply of the doubler laminate are being prepared for eventual doubler fabrication. Boron prepreg material has been ordered for the fabrication of prototype doublers. The stub blade will be utilized as the tool on which the doublers will be laid up and cured.

Doublers will be designed initially based on the data obtained from the subscale specimen test program. The doubler design will be modified as required based on the performance of the stub blade fatigue specimens.

During this phase of the program we will develop and utilize the doubler manufacturing techniques and the doubler bonding procedures that would ultimately be required should field application of the bonded doubler fix be adopted.

SECTION V

PHASE IV. APPLICATION OF BONDED DOUBLERS TO WHIRL
TOWER TEST BLADES

Boron epoxy laminate doublers with stainless steel foil erosion protection will be manufactured by the Air Force Materials Laboratory for this phase of the program. Bonding techniques suitable for use in the field application of the doublers will be utilized. Prototype equipment for use in the bonding operation will be developed, fabricated, and evaluated in this phase of the program.

The thermo-photochromic NDT paint system will be utilized throughout Phases III and IV both in the detection of voids and flaws in the manufacture and bonding of the doublers and to detect and monitor the development and growth of debonds during whirl tower testing of the blades.

SECTION VI

PHASE V. DOUBLER FIELD INSTALLATION KIT

Upon successful completion of program Phases III, IV, and V and approval from SD, EN, and the cognizant AMA, a field installation kit for the adhesive bonding of boron epoxy doublers to the H-3 blade tip will be assembled. Specifications for the manufacture of doublers (NDT and QC will be included) and the bonding procedures will be written. Complete photo coverage of the entire process will be made available with the kit instruction manual. Equipment and instructions for use of the NDT paint will be included. The kit will be designed for the simultaneous field installation of doublers to the five blades of an H-3 aircraft.

SECTION VII

DISCUSSION AND CONCLUSIONS

The purpose of this project is to establish the feasibility of the use of an adhesive bonded doubler to prevent crack formation around stress concentrations and to retard the growth of cracks already present in a metal substructure. Specifically, the program goals are to provide a field fix solution to the tip cracking problems encountered in the H-3 helicopter main rotor spar. Subscale test specimens of two types are being tested in order to demonstrate the effectiveness and reliability of an adhesive bonded doubler, and to develop quantitative design information for the application of the doubler to the helicopter spar.

It was obvious that since this is a stiffness critical problem the highest modulus, lowest density doubler materials would provide lightest doublers with the least thickness built-up in the blade tip airfoil section. The application is a natural for near unidirectional high modulus composites.

The primary approach to the design and analysis of the bonded doubler solution to this problem is empirical. The data generated in the subscale specimen testing will design the doubler to be utilized on the stub blade static and fatigue tests. This design will be modified as required by the stub blade testing before the doublers are applied to the whirl tower test blades.

The preliminary doubler stress analysis was based on a strength and stiffness of materials approach. Materials thickness, stress distributions, locations of peak stresses, and stress concentration effects were all estimated via hand calculations utilizing the techniques in the references to this report.

A companion analytical effort is in progress to develop a much more refined picture of the stresses and strains in the bonded doubler specimen and stub blade via finite element analysis techniques.

It is well known that the stress and strain distribution in composite materials is inherently complicated by the joining of elements having dissimilar strength and stiffness response characteristics. The stress and strain distributions due to geometrical configurations and constraints are complicated by the material anisotropic elastic characteristics. Further, the re-distribution of such stresses due to the repetition of loads in a fatigue environment is a completely unknown quantity. Therefore, the initial picture of the stresses and strains in our subscale specimens may change significantly due to the load environment encountered.

The problems inherent in the design and stress analysis of the adhesive bonded joint for the doubler to substructure bond are also complicated by the fact that the doubler is a composite. Unfortunately, at the present time, there are no rational design procedures available for bonded joints involving composites. We know that the Volkerson and Goland and Reissner types of analysis consistently predict higher stress concentrations than those observed experimentally. The present analyses

do not consider the micro and macro mechanical behavior of the composite adherend. Since both the adhesive and the composite are viscoelastic materials, it is evident that composite joint design must combine the analysis of the adherend and adhesive with failure criteria for both. The finite element method provides the analysis technique for both the composite adherend and the adhesive. Work is in progress to supplement this analysis with realistic materials properties data. No work will be attempted to supply failure criteria inputs to this analysis.

The joint design approach is empirical, involving the development of shear strength-joint parameter data, using this data as a guide for adhesive and surface preparation selection and overlap design; then building a part and testing it.

Figure 10 is a drawing of the tip of the H-3 main rotor spar showing the location of the rivet holes, the thrust from the leading edge weight, and the tip cap and balance weight retention blocks. Also identified, are the locations of complete chordwise cracks formed in two spars during flight. In one incident the blade tip was lost completely in flight. The aircraft was in a landing mode at about 40 feet in altitude and landed safely.

All of the analyses and specimen testing performed to date, has shown that the use of an adhesive bonded boron epoxy laminate doubler applied as a field fix is both feasible and practical.

Specimen testing has shown that the bonded doubler is capable of preventing crack formation from occurring in specimens which had no detectable cracks before doubler application. Also, the doubler should be capable of preventing the growth of cracks which pre-existed in the specimen prior to doubler application. This is dependent upon the stresses induced into the spar on cool down. In both of these cases, specimens have been fatigue cycled to more than 1×10^7 cycles.

Figure 11 shows a proposed mode of operation of a doubler bonded to the substrate. The load in the substructure is picked up by shear lag through the bond into the doubler at a rate depending on the modulus and thickness of the doubler and the shear modulus of the adhesive. The local reduction of load (and stress) in the area of the crack or rivet hole in this case reduces the stress-intensity in the substrate.

Testing has shown that the adhesive is capable of surviving in the complex stress and strain fields around the rivet holes and cracks. This work has also shown that in the event that the substructure doubler area is overloaded or the doubler is underdesigned the cracks in the substructure will grow but will not propagate into the doubler. In this event, provided the adhesive bond is adequately designed, the doubler should be capable of transferring the loads across the completely failed substrate.

BONDED DOUBLER FIX FOR H-3 ROTOR SPAR

In-House Specimen Test Plan

Objectives:

- (1) To duplicate, under controlled conditions using 6061-T6 specimens (Figure 1) the cracks that have been found around the rivet holes at the tip of the 6061-T6 spar.
- (2) To demonstrate that 6061-T6 specimens, which do not have pre-existing cracks and to which adhesive bonded doublers have been applied, (Figure 2), will not develop cracks under the load levels in the H-3 spar tip.
- (3) To demonstrate that adhesive bonded doublers, applied to 6061-T6 specimens which have pre-existing cracks, will prevent crack growth under the load levels in the H-3 spar tip.

Approach:

Testing: Specimens of the configuration of Figure 1 will be tested under conditions of mean tensile load fatigue, R ratios of 0.3 to 0.4 at a mean stress of about 7500 PSI.

Static tensile and fatigue testing will be accomplished on specimens in order to determine base line performance for comparison with specimens to which bonded composite doublers have been applied.

Specimen testing will be performed according to the attached specimen test plan.

NDT (1) X Ray NDT will be utilized to determine the propagation of cracks under the bonded doublers.

(2) Dye penetrant will be utilized to inspect specimens for pre-existing cracks and to detect cracks during fatigue loading.

(3) Ultrasonics (Fokker) and photochromic coatings will be utilized to detect voids and debonds in the bonded area of the doubler.

(4) Dye penetrate will be utilized to detect cracks in the composite doubler.

EXP. S.A.

(1) Stress coat will be utilized on specimens, both with and without bonded doublers, in order to locate areas of high strain.

(2) Strain gages will be utilized to monitor strains during static and fatigue testing.

(3) Photo-stress will be utilized over bonded doublers in order to detect areas of stress concentration.

TABLE I
SUBSCALE SPECIMEN TEST PLAN

40 Specimens available

- | | | |
|----|------------------|-----------------------------------------------|
| I. | (1) Tensile Test | 3 specimens (controls) |
| | (2) Tensile Test | 3 specimens (pre-cracked) |
| | (3) Fatigue Test | 3 specimens controls 7500 \pm 4500 PSI |
| | (4) Fatigue Test | 3 specimens (pre-cracked) 7500 \pm 4500 PSI |
-

II. Specimens with Bonded Graphite/Epoxy Doublers

- | | | |
|--|-------------------|-----------------------------------------------|
| | (1) Tensile Test | 3 specimens (controls) |
| | (2) Tensile Test | 3 specimens (pre-cracked) |
| | (3) *Fatigue Test | 3 specimens 7500 \pm 4500 PSI |
| | (4) *Fatigue Test | 3 specimens (pre-cracked) 7500 \pm 4500 PSI |
-

*Cracked prior to doubler bonding

III. Environmental Exposure of Specimens with Doublers

Twelve specimens exposed (unstressed) 30 days @ 120°F - 100% R.T.

Repeat tests 1 through 4 of II above.

IV. Four specimens exposed (stressed) to outdoor environment for 30 days

2240 lbs load on specimen.

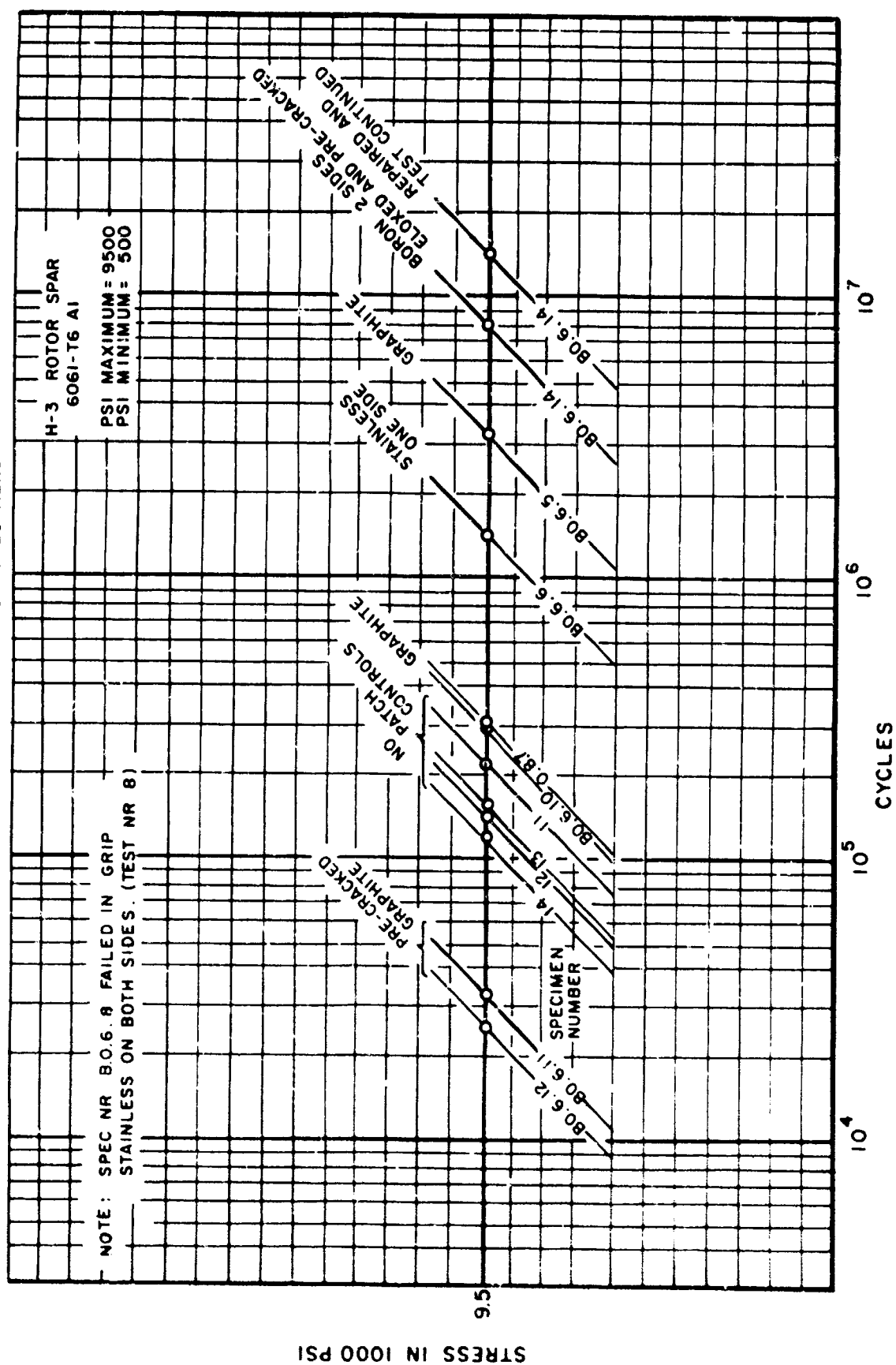
- | | |
|-------------------|-------------|
| (1) Tensile Tests | 4 specimens |
|-------------------|-------------|

V. Specimens are included in the above test program in which the

rivet holes are loaded to levels comparable to those found in the

H-3 spar tip.

TABLE II
S/N DATA ON FOUR HOLE FATIGUE SPECIMENS



TEST LABORATORY DATA SHEET ON FOUR HOLE FATIGUE SPECIMENS

[illegible]

TABLE IV
DOUBLER LAMINATES AND BONDED FATIGUE SPECIMENS PRODUCED TO DATE

AE9-62 : 0.6 HELICOPTER FIELD REPAIR BONDING SHEET				
LAMINATE NO.	TYPE REINFORCEMENT	SPEC NO.	TYPE	PATCH
0.6.1	12 PLY, GRT-70-350A ($4\frac{1}{4}$ " x $4\frac{1}{4}$ ")	BO.6.1	GRT-70-350A, (0.6.1)	(3" x $4\frac{1}{4}$ ")
0.6.2	18 PLY, GRT-70-350A (9" x 9")	BO.6.2	GRT-70-350A, (0.6.2a)	(3" x 9")
0.6.3	18 PLY, GRT-70-350A (9" x 9")	BO.6.3	301 $\frac{1}{4}$ HARD S.S. (3" x 5")	
0.6.4	18 PLY, BORON FIBER (9" x 9")	BO.6.4	NO PATCH	
0.6.5	20 PLY, GRT-70-350A (9" x 9")	BO.6.5	GRT-70-350A, (0.6.2b)	(3" x 9")
0.6.6	18 PLY, BORON FIBER (9" x 9")	BO.6.6	301 $\frac{1}{4}$ HARD S.S. (3" x 5")	
0.6.7	9 PLY, BORON FIBER (9" x 9")	BO.6.7	GRT-70-350A, (0.6.2c)	(3" x 9")
0.6.8	9 PLY, BORON FIBER (9" x 9")	BO.6.8	301 $\frac{1}{4}$ HARD S.S., BOTH SIDES	
		BO.6.9	BORON, BOTH SIDES, (0.6.4a, 0.6.4b)	(3" x 9")
		BO.6.10	GRT-70-350A, (0.6.5b)	(3" x 9")
		BO.6.11	GRT-70-350A, (0.6.5a)	(3" x 9")
		BO.6.12	GRT-70-350A, (0.6.5c)	(3" x 9")
		BO.6.13	BORON, BOTH SIDES, (0.6.7a, 0.6.8a)	(3" x 9")
		BO.6.14	BORON, BOTH SIDES, (0.6.7b, 0.6.8b)	(3" x 9")
		BO.6.15	BORON, BOTH SIDES, (0.6.7c, 0.6.8c)	(3" x 9")
		BO.6.16	BORON, BOTH SIDES, (0.6.6a, 0.6.6b)	(3" x 9")

PROGRAM SCHEDULE

28

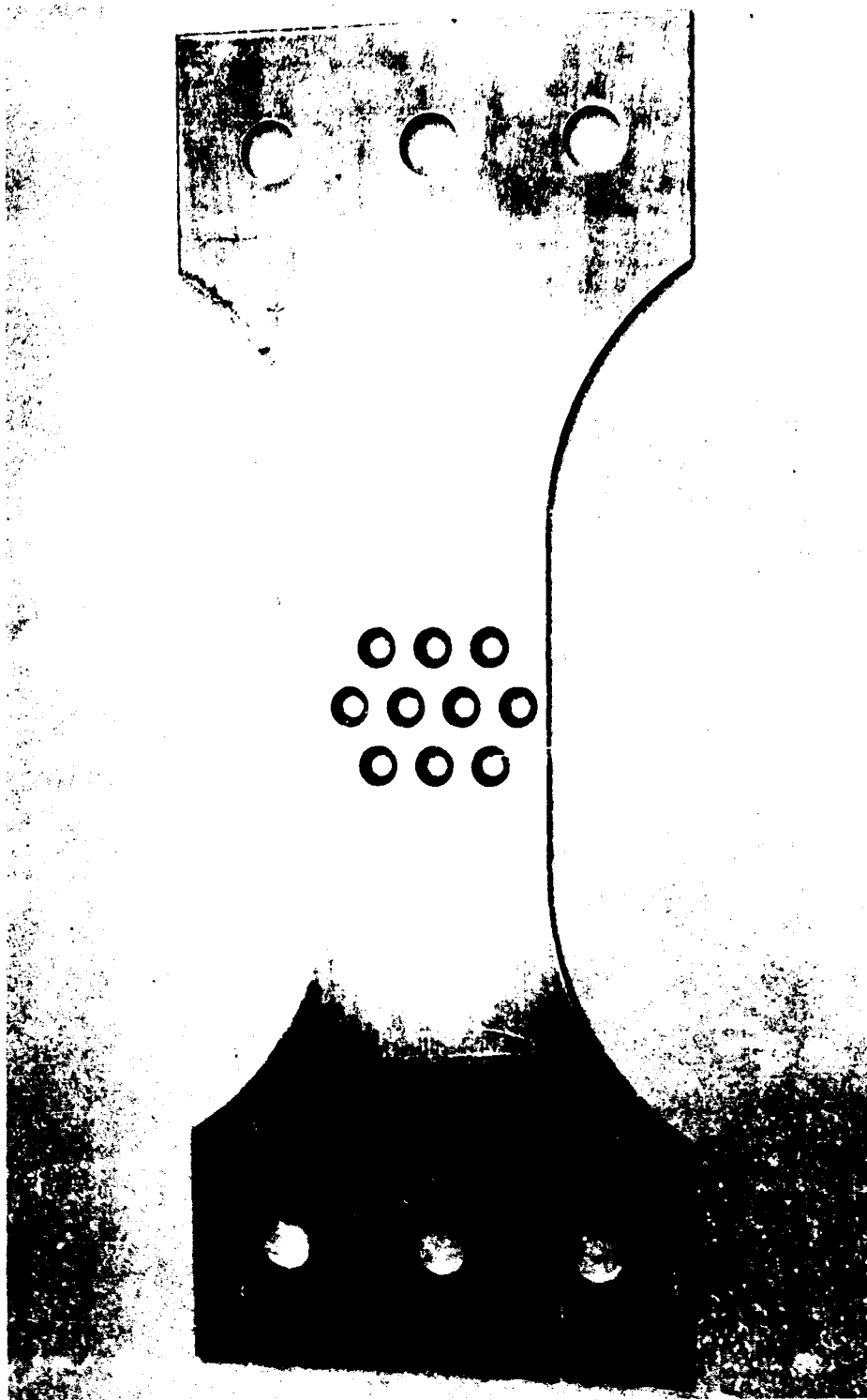


Figure 1. 6061-T6 Specimen with Ten Hole Rivet Pattern

AFML-TR-70-241

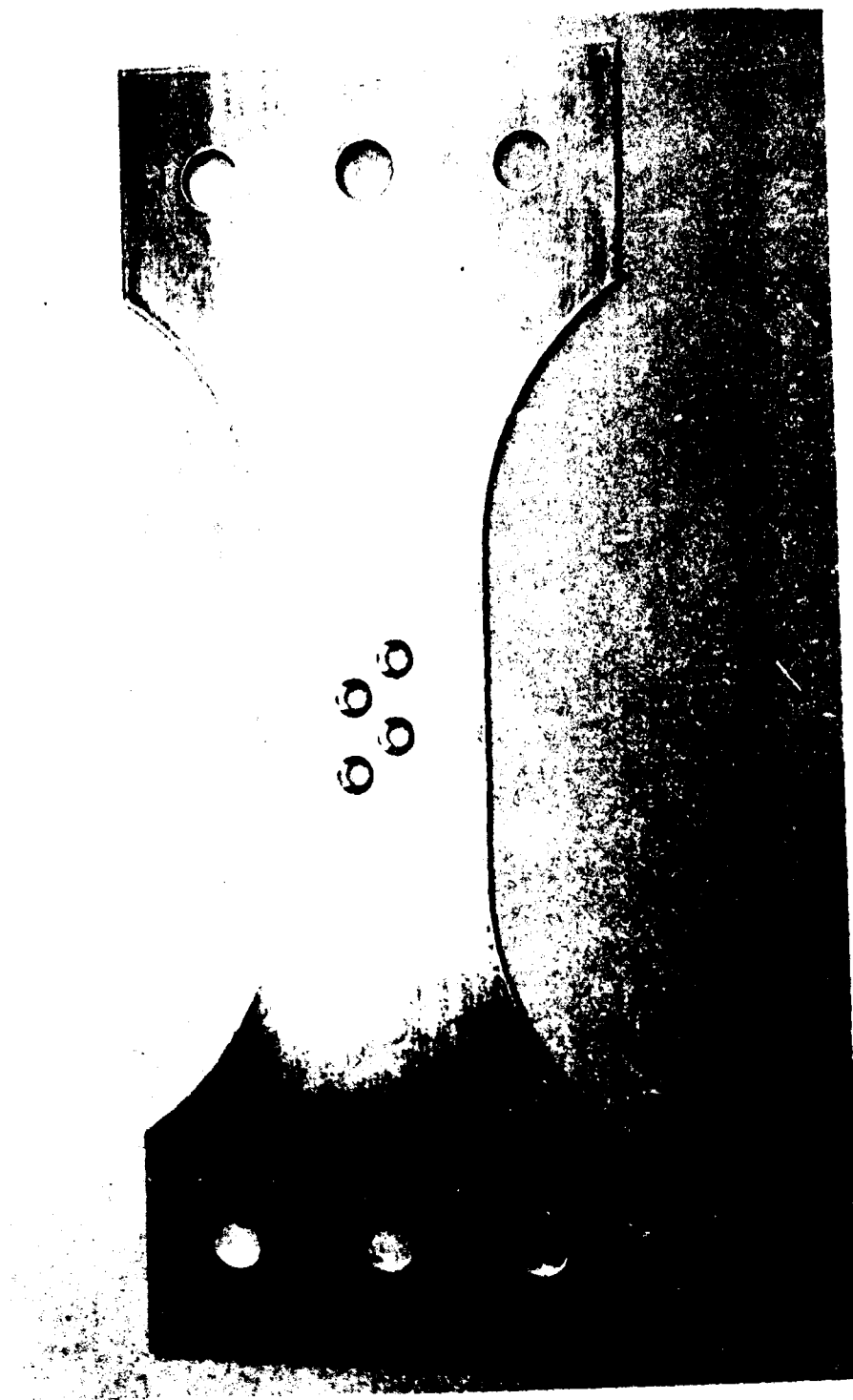


Figure 2. 6061-T6 Specimen with Four Hole Rivet Pattern

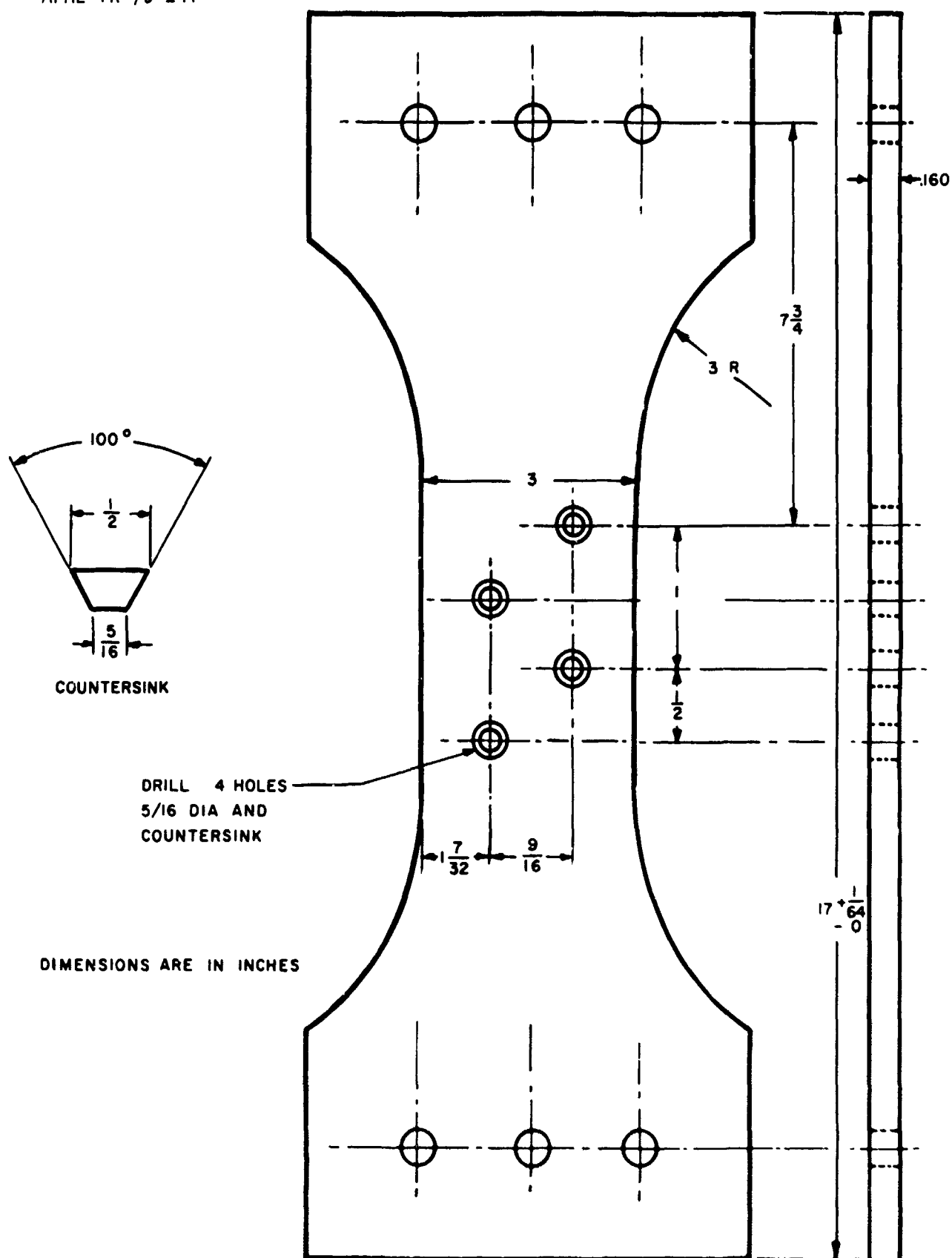


Figure 3. Dimensional Drawing of Fatigue Test Specimens

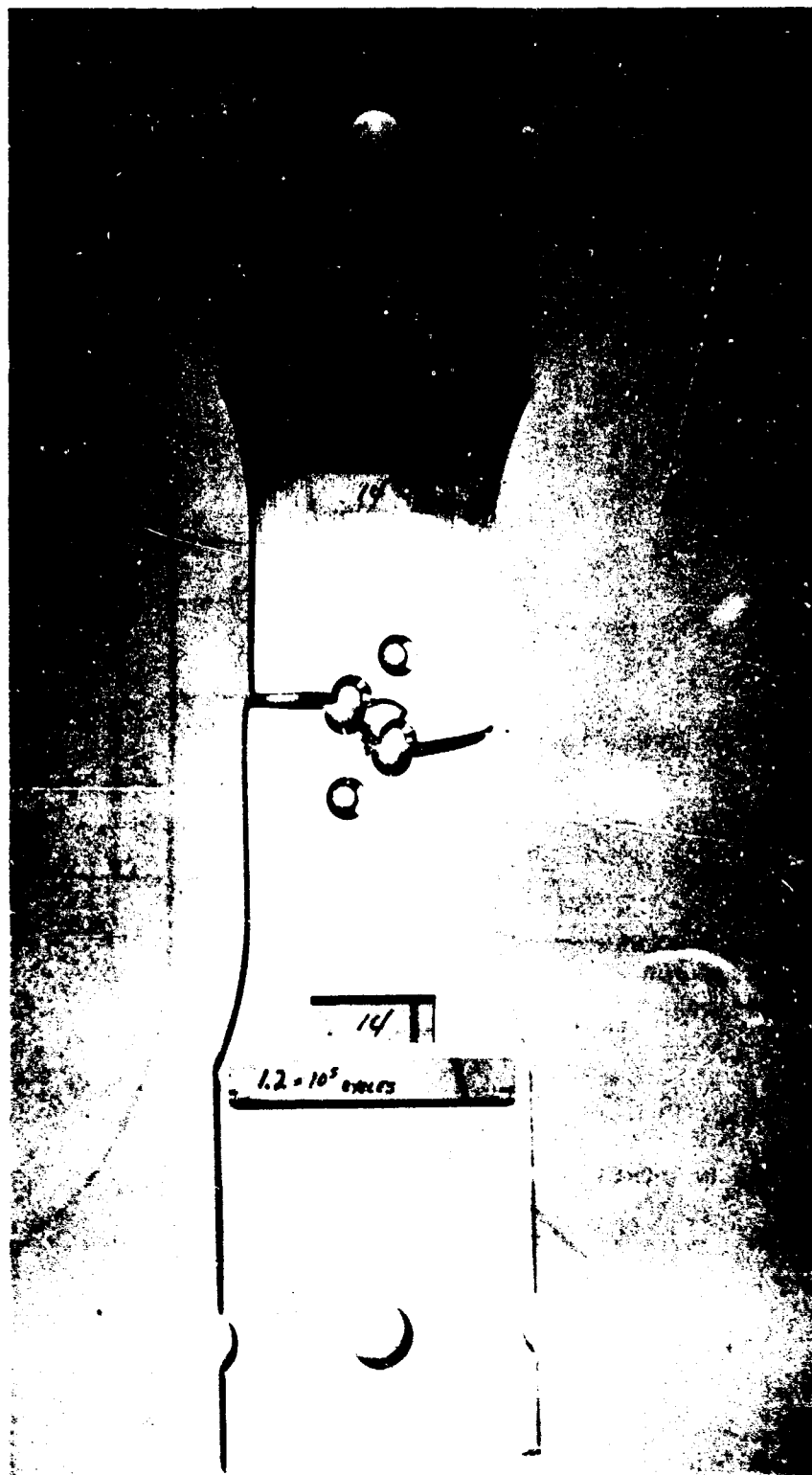


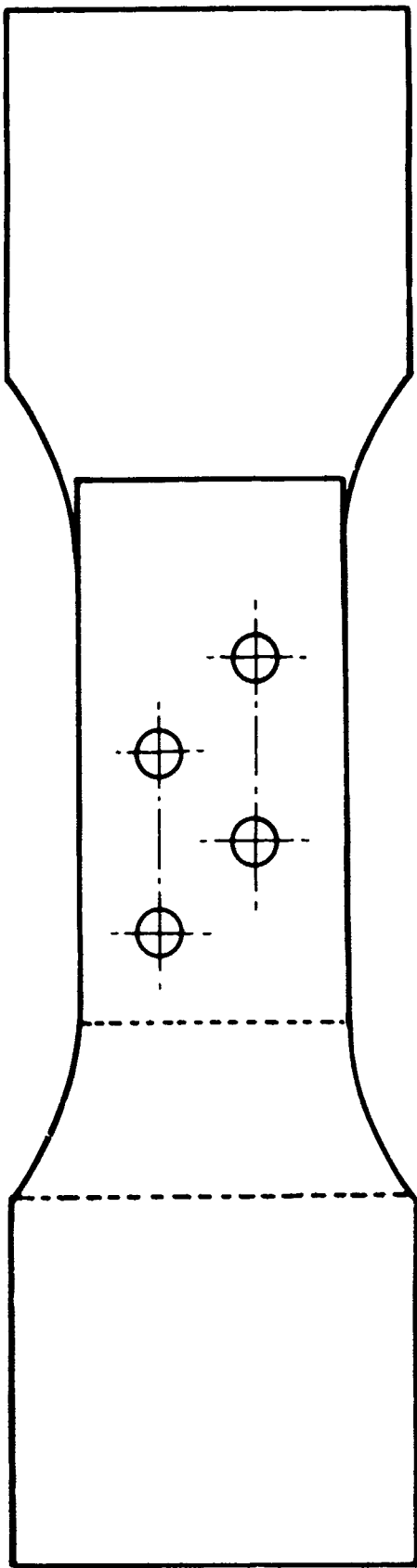
Figure 4. Typical Fatigue Failure of Control Specimen



Figure 5. Grip Failure in Four Hole Fatigue Test Specimen



Figure 6. Application of Photo-Thermochromic NDT Coating to Specimen
Using Schenck Tester



DIMENSIONS ARE IN INCHES

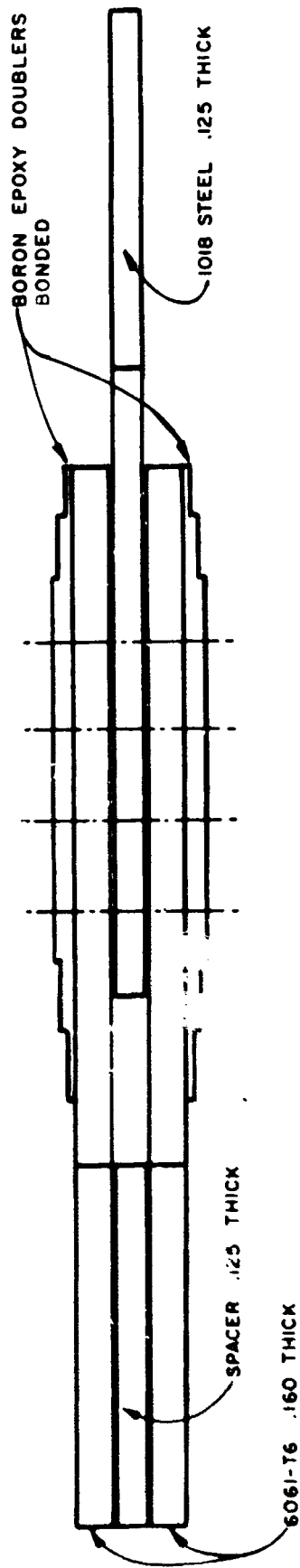


Figure 7. Drawing of Specimen with Loaded Holes, Four Hole Pattern

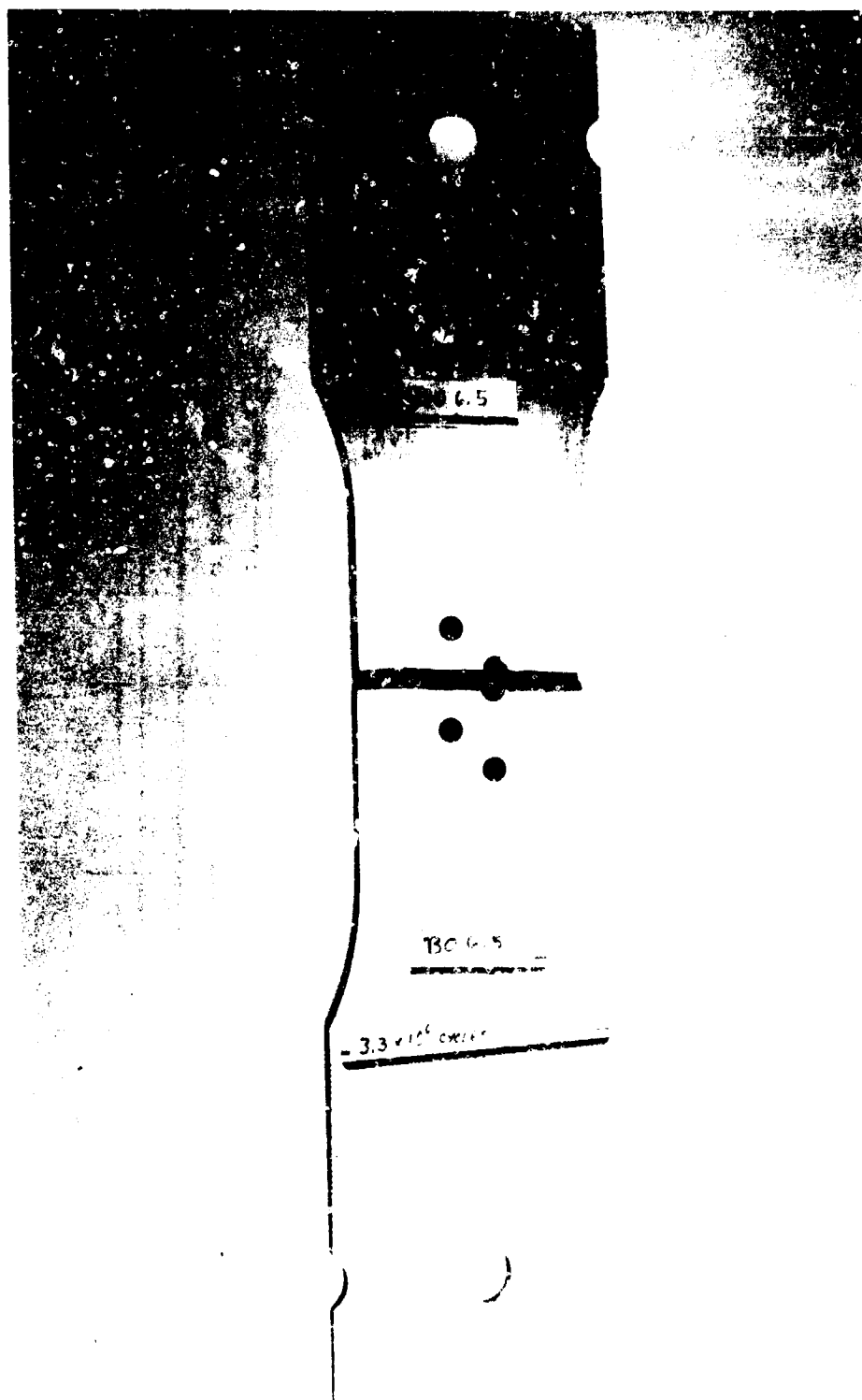


Figure 8. Fatigue Failure, Graphite, Load Applied to One Side Only



Figure 9. Specimen B.O. 6.14 Boron Epoxy Doubler Both Sides,
Specimen Pre-Cracked Prior to Bonding Doublers

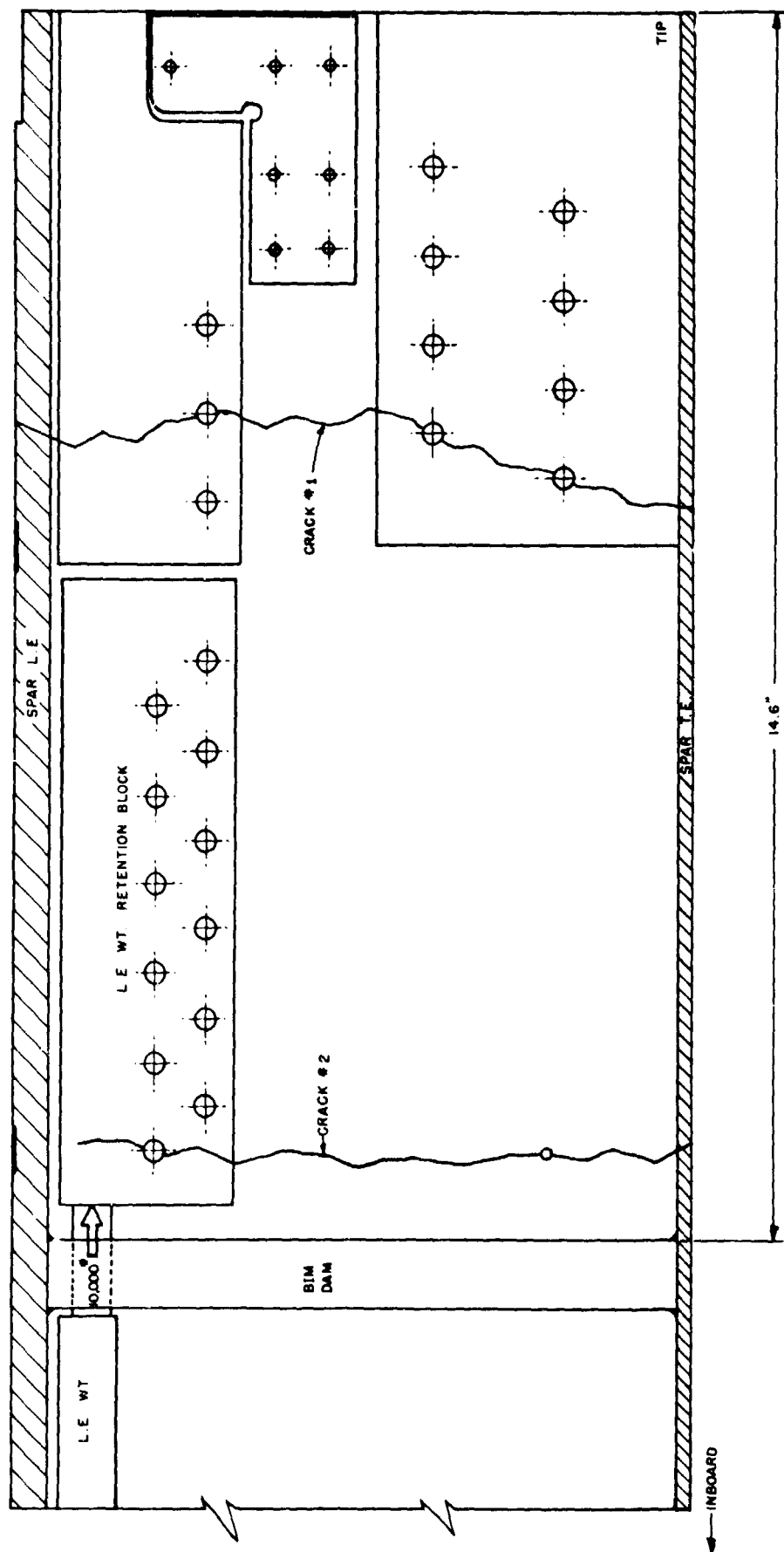


Figure 10. Drawing of H-3 Spar Tip

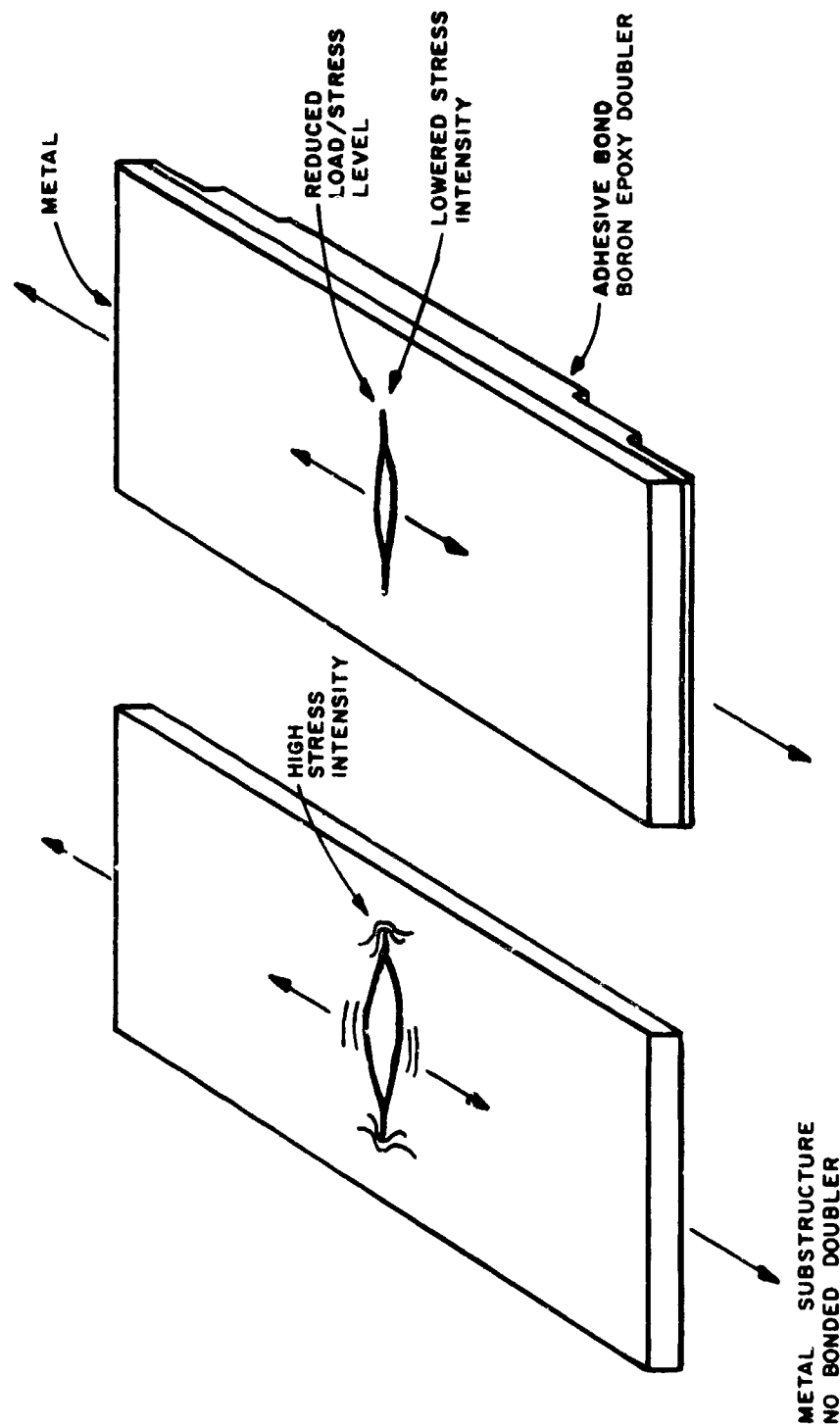


Figure 11. Mechanical Action of Bonded Doubler in Retarding Crack Growth in Metal

REFERENCES

1. K. Boller, Effect of Notches on the Fatigue Strength of Composite Material, AFML TR-69-6, November 1969.
2. T. J. Reinhart, G. Young, and J. Cherry, "Adhesive Bonded Laminated Structures," AFML-TM-69-11, December 1969.
3. D. Kutscha, K. Hofer, Jr., Feasibility of Joining Advanced Composite Flight Vehicle Structures, AFML-TR-68-391, January 1969.
4. Advanced Composites Design Guide, November 1968.
5. MIL-HDBK-17, Composites for Aerospace Vehicles, 1970 Revised Edition, August 1970.

AFML-TR-70-241

APPENDIX
PRELIMINARY DOUBLER ANALYSIS

SYMBOLS

δ	-	elongation in/in
σ	-	stress PSI
E	-	Youngs Modulus PSI
P_T	-	total load lbs
A	-	area in ²
l	-	length in
P_{Al}	-	Load in aluminum lbs
P_D	-	Load in doubler lbs
α	-	Linear Coefficient of thermal Exp. in/in/°F
ΔT	-	Temperature change °F
τ	-	Adhesive shear stress PSI
W	-	Bonded joint width in

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1. Preliminary doubler requirements were derived based on the steady state plus vibratory loads received from ENJER. The loads 5000 PSI steady and 4500 PSI alternating were derived from an instrumented flight test conducted by the helicopter manufacturer. The peak load of 9500 PSI was utilized with a safety factor, about 1.5 to come up with the doubler design stress of 14,000 PSI. The doubler is designed to maintain the peak stresses in the aluminum (steady state plus vibratory) at a value less than or equal to 5000 PSI at all times. The adhesive bond is designed to carry the tensile and bending loads in the event of complete spar failure. The safety factor was applied strictly because of our inability to analytically predict the influence of relaxation, creep, and static fatigue on the load transfer capabilities and strength of the adhesive bonded joint and the true level of the thermally induced stresses.

2. The tensile loads required to produce a stress of 14,000 PSI in the four hole aluminum specimen are calculated as follows:

$$\delta = \frac{\sigma}{E} = \frac{14,000}{10 \times 10^6} = 1.4 \times 10^{-3} \text{ in/in} \quad l = 4.75 \text{ in}$$

$$\delta_{(4.75)} = (1.4)(4.75) \times 10^{-3} \text{ in} = 6.65 \times 10^{-3} \text{ in}$$

$$P_T = \frac{\delta AE}{L} = \frac{(1.4)(4.75) \times 10^{-3} (.41)(10 \times 10^6)}{4.75}$$

$$P_T = 5750 \text{ lbs}$$

The elongation (δ) in the aluminum specimen at the 5000 PSI peak stress would be:

$$\delta = \frac{\sigma}{E} = \frac{5000}{10 \times 10^6} = 5 \times 10^{-4} \text{ in/in}$$

$$P_{Al} = \frac{\delta AE}{L} = \frac{(5 \times 10^{-4})(4.75)(.41)(10 \times 10^6)}{4.75}$$

$$P_{Al} = 2060 \text{ lbs}$$

Since the aluminum substrate must be limited to a strain of 5×10^{-4} in/in and the total force to be carried is:

$$P_T = P_{Al} + P_D$$

$$P_D = P_T - P_{Al}$$

$$P_D = 5750 - 2060$$

$$P_D = 3690 \text{ lbs}$$

This is the load that the doubler must carry at a strain of 5×10^{-4} in/in.

If we assume that the doubler remains bonded to the aluminum substrate and if we neglect creep and stress relaxation in the adhesive and the composite doubler and the thermally induced stresses, the elongation of the doubler and substrate are equal.

$$\delta_{Al} = \delta_o = 5 \times 10^{-4} \text{ in/in}$$

The relation between the cross-sectional area and modulus of the doubler is given by:

$$AE = \frac{P_L}{\delta} = \frac{3960 \cdot 4.75}{5 \times 10^{-4} \cdot 4.75} = 7.94 \times 10^6 \text{ lbs}$$

$$A = \frac{7.94 \times 10^6}{E} \text{ in}^2$$

Table VI of this appendix shows the doubler parameters obtained utilizing the above relationship. As can be seen, the thickness buildup obtained using S Glass epoxy composites is unacceptable.* The graphite materials suffer due to the mismatch of thermal expansion and the weight of the stainless steel is excessive. This leaves the boron epoxy materials as one of the only promising doubler materials, however, even here the thermal stress problem is serious. With the SP 272 boron/epoxy prepreg material we obtain about .0053 inches of laminate thickness per ply. 0.088 inches of laminate requires 16.7 plies. We have selected an 18-ply balanced layup in the test section. This gives us an 0.096-inch thick doubler which will function properly even if two or three plies are damaged. Table VIII shows typical properties values for the boron epoxy laminate selected.

3. Shear loads in the adhesive bond are calculated by the differences in the sheet tensile forces between the doubler and the substrate.

Figure 12 illustrates the doubler application.

$$\text{Adhesive Shear Force } F_{ad} = \tau W X$$

$$\text{Sheet Tensile Force } F_T = \sigma T W$$

$$F_{ad} = F_T \text{ doubler} - F_T \text{ Aluminum}$$

$$\tau W X = \sigma_D t_D W_D - \sigma_{Al} t_{Al} W_{Al}$$

$$\text{since } W_D = W_{Al}$$

$$\tau X = 3697 - 2060 = 1630 \text{ lbs/in}$$

*Severe aerodynamic penalties are incurred as the cross section of the blade tip is increased. Therefore, minimum thickness buildup is desirable. Otherwise S Glass epoxy composites would make a very good doubler material.

In this case X is one-half of the effective doubler length (doubler length minus any taper) $\lambda = 4.75/2 = 2.37$

$$\tau = 1630 / 2.37 = 690 \text{ lbs/in}^2$$

If we assume complete failure of the aluminum spar we equate the adhesive shear force to the tensile force in the doubler. In this case the doubler carries the entire load, and is working under a tensile stress of 22,000 PSI (5750 lbs).

$$\tau W X = \sigma_D t_D W_D$$

$$\tau X = 5750 \text{ lbs/in}$$

$$\tau = \frac{5750 \text{ lbs/in}}{2.37 \text{ in}}$$

$$\tau = 2420 \text{ lbs/in}$$

This stress is a bit high, but may easily be reduced if so desired by increasing the effective length of the patch.

These calculations indicate that with the spar intact the adhesive stresses, about 700 PSI shear, are quite low. The adhesive bond would be expected to function at this stress level for at least 10^8 cycles. Should complete spar failure occur drastic changes in the load paths and local reduction in stiffness would seriously complicate the problem.

Stress concentrations will occur at the juncture of the crack and the doubler. Experimental work in AFML-TR-68-398 and Reference 2 has shown that the experimentally measured stress concentrations of about 2 to 2.7 are about half those predicted by linear analysis four to six. Experimental work has shown that local plastic flow in the high stress regions relieves stress buildups due to high differential straining, depending upon the type of adhesive selected.

4. Thermal stresses - stresses induced as a result of differences in coefficients of thermal expansion upon cool down from the adhesive curing temperature, can be estimated from the deformation equation of the bonded assembly assuming a force equilibrium exists.

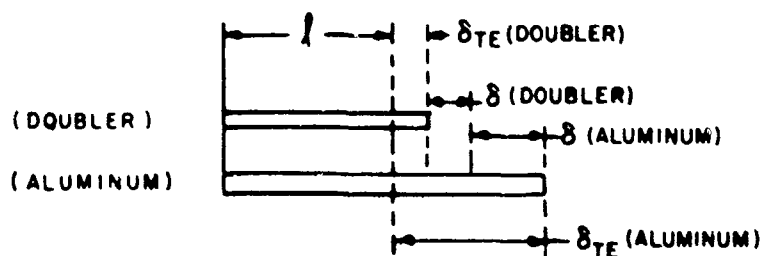
It was known from the beginning that the stresses set up in bonding a graphite epoxy doubler to the aluminum substrate, using a heat curing adhesive, would be unacceptably high. It was also known that we could not hope to obtain the best adhesive properties using room temperature curing adhesives. The following calculations show our first estimates of the thermally induced stresses:

Assumptions:

- (1) Zero stress state occurs at 220°F (250°F cure)
- (2) -65°F is lowest operating temperature $\Delta T = 285^\circ\text{F}$
- (3) C.T.E. of aluminum and doubler constant over ΔT
- (4) Doubler remains bonded to substrate

$$P_{\text{Aluminum}} = -P_{\text{Doubler}} \quad (\text{at any temperature})$$

The deformation equation is:



$$\delta_{TE} \text{ Doubler} + \delta \text{ Doubler} = \delta_{TE} \text{ Aluminum} - \delta \text{ Aluminum}$$

$$\frac{\text{doubler}}{\alpha L \Delta T + \frac{PL}{AE}} = \frac{\text{aluminum}}{\alpha L \Delta T + \frac{PL}{AE}}$$

Since $P_{\text{Doubler}} = -P_{\text{Aluminum}}$ we can substitute and solve for either one:

$$(\alpha L \Delta T)_{\text{Doubler}} - \frac{P_{A2} L}{A_D E_D} = (\alpha L \Delta T)_{\text{Aluminum}} - \frac{(P_{A1})}{A_{A1} E_{A1}}$$

$$\left(\frac{P_{A1} L}{A_{A1} E_{A1}} - \frac{P_{A2} L}{A_D E_D} = (\alpha L \Delta T)_{\text{Aluminum}} - (\alpha L \Delta T)_{\text{Doubler}} \right)$$

$$P_{A1} L \left(\frac{1}{A_{A1} E_{A1}} - \frac{1}{A_D E_D} \right) = (\alpha_{A1} - \alpha_D) \Delta T L$$

$$P_{A1} = \Delta T \frac{(\alpha_{A1} - \alpha_D)}{\frac{1}{A_{A1} E_{A1}} - \frac{1}{A_D E_D}}$$

Case 1 Graphite Epoxy Doubler (250° Cure)

$$E_{A1} = 10 \times 10^6 \text{ PSI}$$

$$E_{GE} = 30 \times 10^6 \text{ PSI}$$

$$\alpha_{A1} = 13 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

$$\alpha_{GE} = 1.5 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

$$A_{A1} = .48 \text{ in}^2$$

$$A_{GE} = .30 \text{ in}^2$$

$$\Delta T = 285^\circ\text{F}$$

$$L = 5$$

Table VII shows the typical properties of the graphite epoxy laminate selected

$$\text{Since } P_{A1} = \Delta T \frac{(\alpha_{A1} - \alpha_{GE})}{\frac{1}{A_{A1} E_{A1}} - \frac{1}{A_{GE} E_{GE}}}$$

$$P_{A1} = 285 \frac{(13 \times 10^{-6} - 1.5 \times 10^{-6})}{\frac{1}{(.48)(10 \times 10^6)} - \frac{1}{(.30)(30 \times 10^6)}}$$

$$P_{A1} = 285 \frac{11.5 \times 10^{-6}}{\frac{1}{4.8 \times 10^6} - \frac{1}{9 \times 10^6}}$$

$$P_{A1} = 285 \frac{11.5 \times 10^{-6}}{(.208 - .111) \times 10^{-6}}$$

$$P_{A1} = 285 \frac{11.5 \times 10^{-6}}{.097 \times 10^{-6}} = 285(119)$$

$$P_{A1} = 34,000 \text{ lbs (tension)}$$

Then since $P_{A1} = P_{\text{Doubler}}$

$$P_{GE} = 34,000 \text{ lbs (compression)}$$

Since $\sigma = P/A$

$$\sigma_{A1} = \frac{34,000}{.48} = 71,000 \text{ PSI}$$

$$\sigma_{GE} = \frac{34,000}{.30} = 113,400 \text{ PSI}$$

These stresses are extremely high and we would anticipate adhesive bond or interlaminar shear failure on the first cool down cycle. The adhesive shear force expected due to these thermal stresses alone would be:

$$\tau LW = 34,000 \quad L=5$$

$$\tau = 34,000/LW \quad W=3$$

$$\tau = 34,000/15$$

$$\tau = 2270 \text{ PSI}$$

If we assume a room temperature cure 80°F we obtain a ΔT of 145°F, upon cool down to -65°F. Using the above procedures the induced thermal loads and stresses are:

$$\begin{aligned} P_{Al} &= 17,200 \text{ lbs (tension)} \\ P_{GE} &= 17,200 \text{ lbs (compression)} \\ \sigma_{Al} &= 36,000 \text{ PSI} \\ \sigma_{GE} &= 57,500 \text{ PSI} \\ \tau &= 1150 \text{ PSI} \end{aligned}$$

Several graphite epoxy bonded specimens were fabricated and tested. One specimen was cycled from -65°F to +180°F in the unloaded condition. This specimen survived about 40 cycles before the adhesive bond failed. Since the mechanical loads add to the stresses in the adhesive and in the aluminum, it was apparent that we would encounter reliability problems with the graphite epoxy doubler.

Case II Stainless Steel Doubler

$$\begin{aligned} E_{ss} &= 30 \times 10^6 \text{ PSI} \\ \alpha_{ss} &= 10 \times 10^{-6} \text{ in/in/}^\circ\text{F} \end{aligned}$$

Using the above methods and a ΔT of 285°F we obtain:

$$\begin{aligned} P_{Al} &= 885 \text{ lbs (tension)} \\ P_{ss} &= 885 \text{ lbs (compression)} \\ \sigma_{Al} &= 1840 \text{ PSI (tension)} \\ \sigma_{ss} &= 2940 \text{ PSI (compression)} \\ \tau &= 60 \text{ PSI (shear)} \end{aligned}$$

Thus we can see that, except for the unacceptable weight penalty incurred, stainless steel is an extremely desirable doubler material.

Case II Boron Epoxy Doubler

$$E_{BE} = 30 \times 10^6 \text{ PSI}$$

$$\alpha_{BE} = 3 \times 10^{-6} \text{ in/in/}^\circ\text{F}$$

Using the above method and a ΔT of 285°F we obtain:

$$P_{A1} = 15,740 \text{ lbs (tension)}$$

$$P_{BE} = 15,740 \text{ lbs (compression)}$$

$$\sigma_{A1} = 32,900 \text{ PSI (tension)}$$

$$\sigma_{BE} = 59,700 \text{ PSI (compression)}$$

$$\tau = 1050 \text{ PSI (shear)}$$

These are very marginally acceptable values for a durable and reliable doubler. During operation at temperatures above an ambient of about 100°F the thermal stresses become negligible and the mechanical loads on the boron epoxy doubler cause most of the stress. As operating temperatures decrease the thermally induced stresses subtract from the mechanically induced stresses in the doubler. At -65°F the doubler load is:

$$\begin{array}{cc} \text{(tension) (mechanical)} & \text{(thermal) (compression)} \end{array}$$

$$3960 \text{ lbs} - 15,740 \text{ lbs} = 11,780 \text{ lbs compression}$$

This reduces to a compressive stress of 44,500 PSI. The resultant adhesive shear stress is 785 PSI; thus the load values obtained under the most severe operating conditions are acceptable. The stresses in the aluminum spar, however, increase to unacceptably high tension values. A back up investigation utilizing beryllium, cross rolled, sheet 0.060 inches thick will be initiated as soon as the sheet material can be procured, cut to the shape, and formed as required.

TABLE VI
DOUBLE PARAMETERS (4.75 INCHES LONG) FOR FOUR HOLE SPECIMEN

MATERIAL	MODULUS (PSI)	CROSS SECT. AREA (in) ²	THICKNESS* (in)	STRESS LEVEL PSI	WEIGHT LBS
S Glass/Epoxy	10 x 10 ⁶	.794	.264	4650	.272 (4.35 oz)
Morganite/Epoxy	20 x 10 ⁶	.397	.132	9300	.108 (1.73 oz)
** Boron/Epoxy	30 x 10 ⁶	.264	.088	14,000	.090 (1.44 oz)
Stainless Steel	30 x 10 ⁶	.264	.088	14,000	.375 (6 oz)
Celconese/Epoxy	40 x 10 ⁶	.198	.066	18,600	.054 (.87 oz)

* Doubler thickness required for each 0.160-inch of aluminum substrate thickness

** Selected doubler

TABLE VII
 PROPERTIES OF $\pm 5^\circ$ GRAPHITE EPOXY DOUBLER

F_{TPL}	=	110.0 KSI
F_{TU}	=	160.0 KSI
E_{TL}	=	30×10^6 PSI
$CTE(\alpha)$	=	1.5×10^{-6} in/in/°F
ρ	=	.057 lbs/in ³

TABLE VIII
 PROPERTIES OF $\pm 5^\circ$ BORON EPOXY DOUBLER

F_{PL}	=	120.3 KSI
F_{TU}	=	190.0 KSI
E_{TL}	=	30×10^6 PSI
* $CTE(\alpha)$	=	3×10^{-6} in/in/°F
ρ	=	.07 lbs/in ³
ν_{LT}	≈	.35 @ 4000 u in/in
$\epsilon_{L_{ult}}$	=	6850 u in/in
$\epsilon_{L_{p1}}$	=	4010 u in/in
ν_f	=	.50
n.p.T	=	.0053

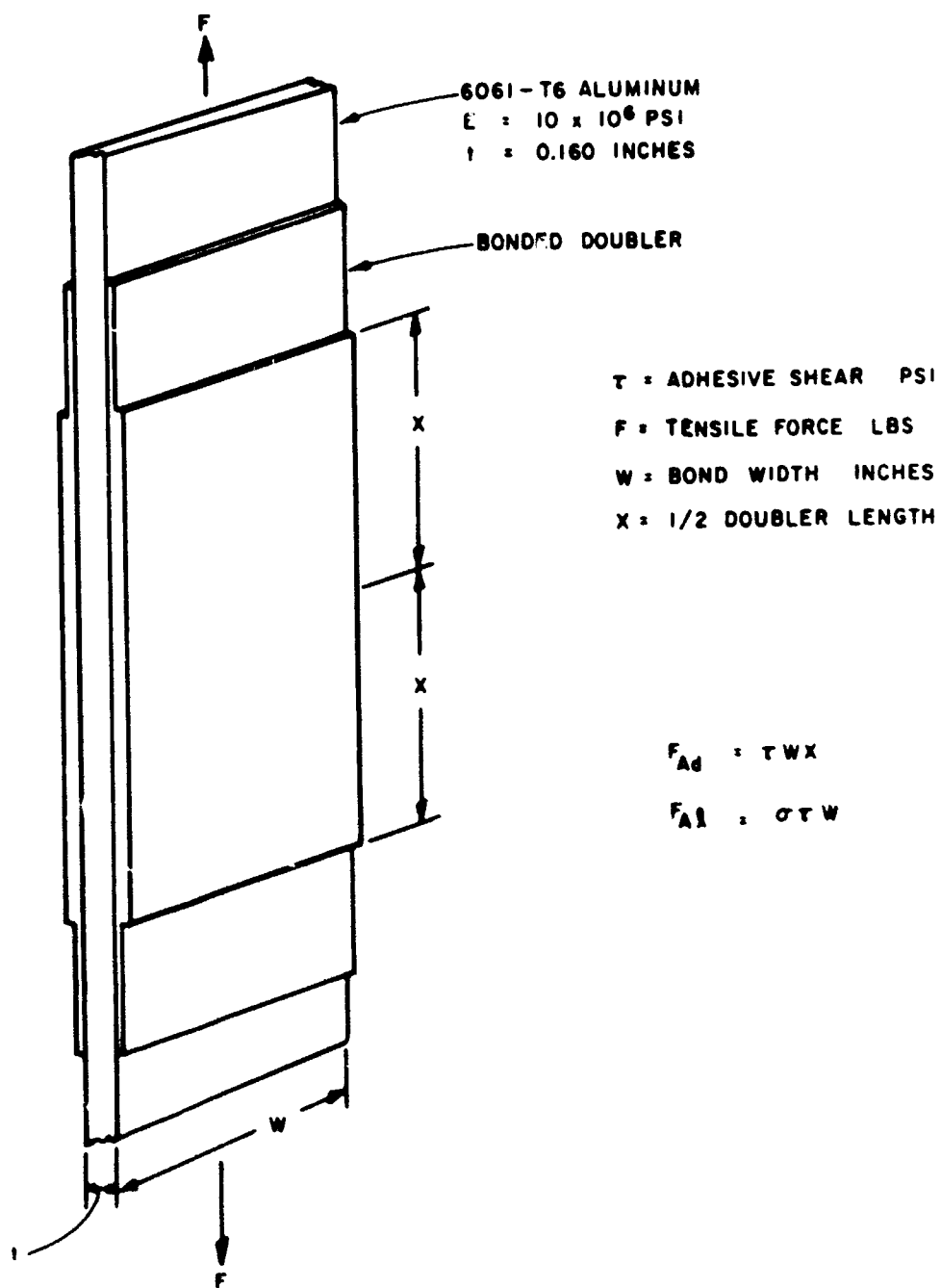


Figure 12. Double Strap Specimen

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Security Classification

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11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Air Force Materials Laboratory (LAE) Air Force Systems Command Wright-Patterson Air Force Base, Ohio 45433	
13. ABSTRACT <p>An in-house program has been initiated in order to demonstrate the feasibility of the use of an adhesive bonded, structural doubler to provide a field fix solution to the problem of crack formation in the rivet holes of the tip of the CH/HH-3C main rotor spar. The program is being conducted in the phases following;</p> <ul style="list-style-type: none">I Doubler Design and AnalysisII Subscale Specimen TestingIII Stub Blade Fatigue TestingIV Whirl Tower Blade TestingV Field Installation Kit <p>The program is designed to demonstrate the effectiveness and reliability of an adhesive bonded doubler in the elimination of crack formation and growth due to stress concentration in a metallic substructure. It is to develop quantitative design information to enable optimization of the doubler and to develop methods for the field application of doublers to the H-3 spar.</p>			

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Security Classification

14	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Adhesive bonding						
	Boron Epoxy Composites						
	Graphite Epoxy Composites						
	6061-T6 Aluminum						
	Fatigue						
	Crack Growth						
	Beryllium						

UNCLASSIFIED

Security Classification